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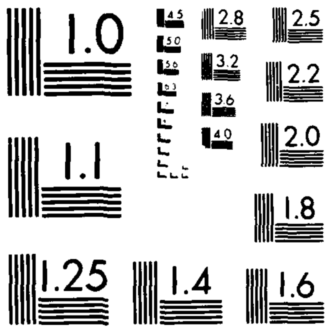

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This work was a study of discharge processes in Knudsen mode (collisionless), thermionic energy converters. Areas of research involve mechanisms for reducing the effects of electron space charge in such devices. Such mechanisms are essential for thermionic converters to produce useful current and power densities. The mechanisms we have chosen to study are: reduction of space-charge through a very close interelectrode gap (less than 10 microns); transport and retention of positive cesium ions generated by surface ionization; transport of positive cesium ions generated in an arc external to the electrodes; and the mechanism for enhanced current output due to a structured emitter in a mixed barium-cesium vapor.

The experimental work used SAVTEC (Self-Adjusting, Versatile Thermionic Energy Converter) diode structures, which were tested in a chamber containing 0.1 - 1.0 torr of cesium vapor. Comparison of measured volt-ampere curves with theory gave excellent agreement and indicated an interelectrode gap of 6.5 microns at an emitter temperature of 1250 K. A theoretical

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model of the collisionless thermionic diode was developed which included surface ionization, auxiliary ions from an external source, and trapping of charged particles in potential wells due to infrequent collisions. Studies showed that trapping of positive ions leads to a large, beneficial increase in current density. Using a diffusion analysis to couple this model to models of collision-dominated discharges gave predictions of the performance of SAVTEC devices in the presence of an auxiliary discharge, and led to design criteria for electrode size in order for auxiliary ionization to be effective. A SAVTEC-type converter with an interelectrode spacing of 18-22 microns was tested over a range of emitter temperatures up to about 1700 K. Maximum performance followed the predictions of vacuum-mode analysis for emitter temperatures below 1580 K. Above that temperature the converter operated in the unignited mode, with partial space-charge neutralization by surface ionization of cesium. It was found that collisionless and diffusion mode theories could be extended into the regime of maximum output power for the unignited mode (spacing and electron mean-free path about equal) to give good agreement with the experimental data.

The Knudsen-mode thermionic converter with a structured emitter was also investigated. A phenomenological analysis of the particle kinetics predicts behavior equalitatively like the published results.

RASOR ASSOCIATES, INC.

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CLOSE-SPACED HIGH TEMPERATURE KNUDSEN FLOW

FINAL REPORT

JUNE 15, 1986

Author

John McVey

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PREPARED BY

RASOR ASSOCIATES
253 Humboldt Ct.
Sunnyvale, CA 94089

87 9 24 109

1.0 INTRODUCTION

1.1 Scientific Objectives

The Knudsen mode of operation in a thermionic energy converter or other thermionic device is that in which the electrons emitted on the average from a thermionic device experience no collisions in crossing the interelectrode space. This requires that the pressure of the vapor (usually cesium) in the interelectrode space is low, or that the spacing between electrodes is small. In order to operate at practical current densities, the effect of electron space charge must be reduced. This can be done through very close interelectrode spacing ($<10\ \mu m$) or the introduction of positive cesium ions. These ions can be produced through surface ionization on the hot emitter surface or can be generated externally and diffuse into the interelectrode space.

Previous development of thermionic energy conversion has emphasized the physics of the ignited mode of operation because operation in the Knudsen regime was impractical with available electrode materials and converter design. Advances in electrode surfaces [1,2] permit low electrode work functions without high cesium pressures, and a new design innovation Self-Adjusting Versatile Thermionic Converter (SAVTEC) permits close interelectrode spacings. New applications which use higher emitter temperatures also make the Knudsen mode practical. As a result, an opportunity now exists to utilize the potentially much higher performance available in the close-spaced Knudsen regime.

The objective of the research was to investigate the various mechanisms, shown in Fig. 1, of charged particle production and transport in the Knudsen mode.

The approach to this investigation is illustrated in Fig. 2. Because the use of probes, electron beams, and other plasma diagnostics is impractical for the very close electrode spacings used, the output characteristics of the device itself, and their behavior with changing conditions, are used as the diagnostic technique. Intercomparison of experimental results with

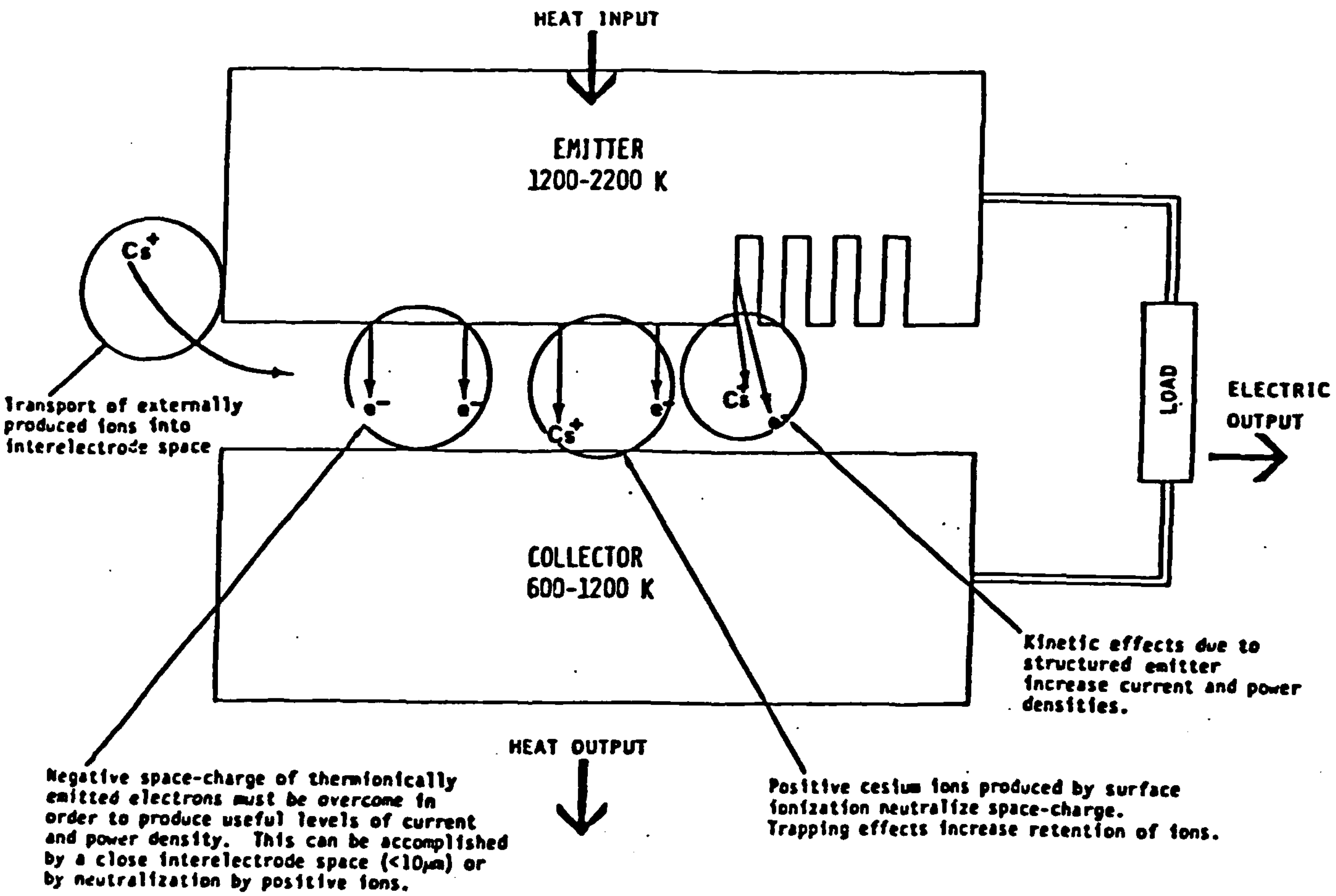


Fig. 1 Discharge Processes in a Knudsen-Mode Thermionic Converter

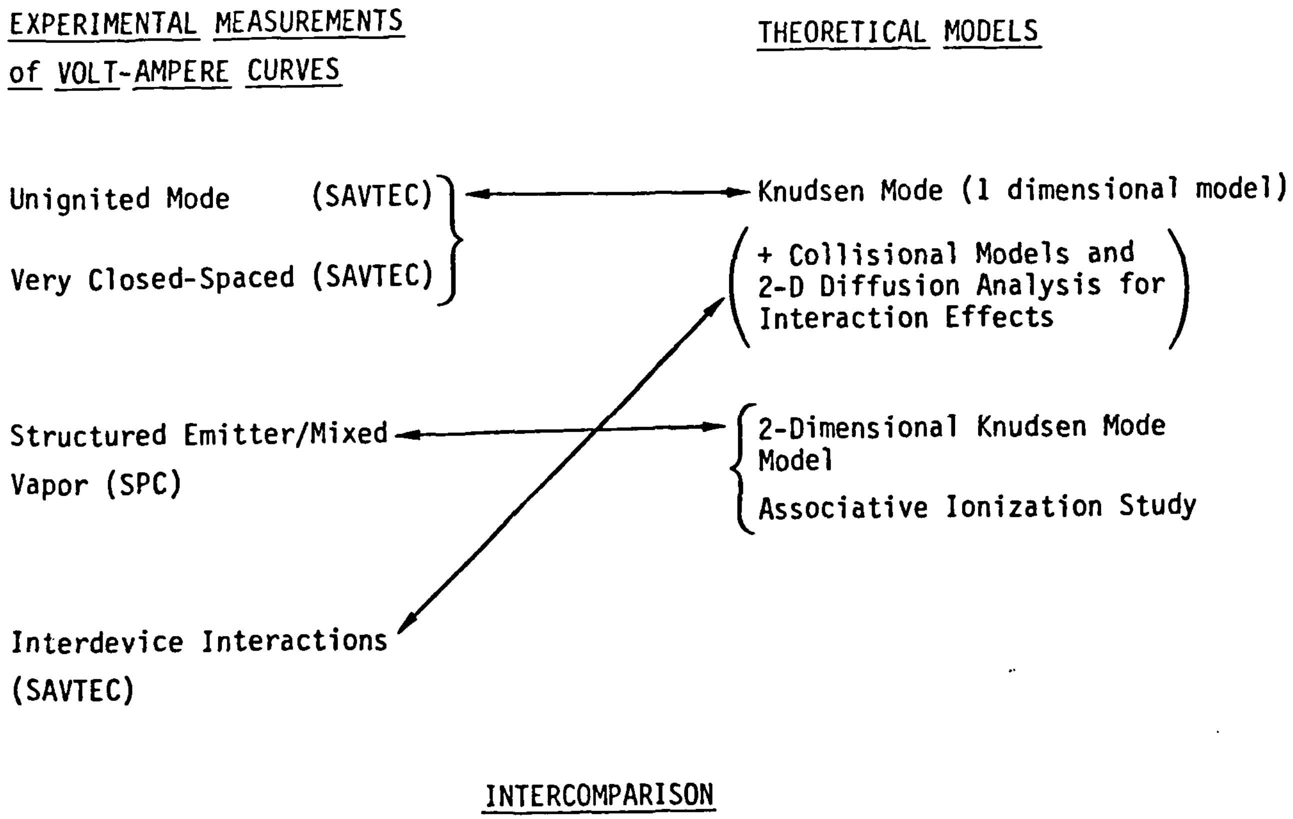


Fig. 2 Research Approach

results from theoretical models confirms our understanding of the dominant mechanisms in the discharge.

In the first process, the effects of space charge are reduced by a very small interelectrode gap. The only charged particles present are electrons, and no plasma is formed. As shown in Fig. 3 the current-voltage characteristic of a close-spaced converter approaches ideal performance as the spacing is decreased. The physics of such a device were first studied by Langmuir [3]. Design considerations have, however, restricted experimental results on such devices to low emitter temperatures and low current densities. The use of SAVTEC converter structures allows very small interelectrode spacings in a practical device configuration and enables experimental measurements at useful current densities.

In the second process, ions are produced in a region external to the converter and diffuse into the electrode space. They can be produced either by electron-atom collisions (ignited mode) or surface ionization (unignited). Since the ions must typically travel a distance of many mean free paths to reach the interelectrode space, they follow collision-dominated transport formulas. Once in the interelectrode space, a collisionless formulation must be used to find the effect on converter output characteristics.

In the third process, positive ions are produced by thermal contact ionization on the emitter surface. The interelectrode potential distributions can have potential wells which, due to infrequent collisions, trap charged particles [4]. Under certain conditions, the potential distribution may be oscillatory in space [5]. Back-emission of electrons from the collector is also important under certain operating conditions.

Soviet researchers have obtained remarkable results in the Knudsen mode with surface ionization by using a structured emitter and a mixed barium-cesium vapor [6,7]. Barium was used to lower the work function of the emitter. Since barium's desorption energy is much higher than that of cesium a much lower pressure is needed to produce the needed ions. Some of their results are shown in Fig. 4. The output current for the converter

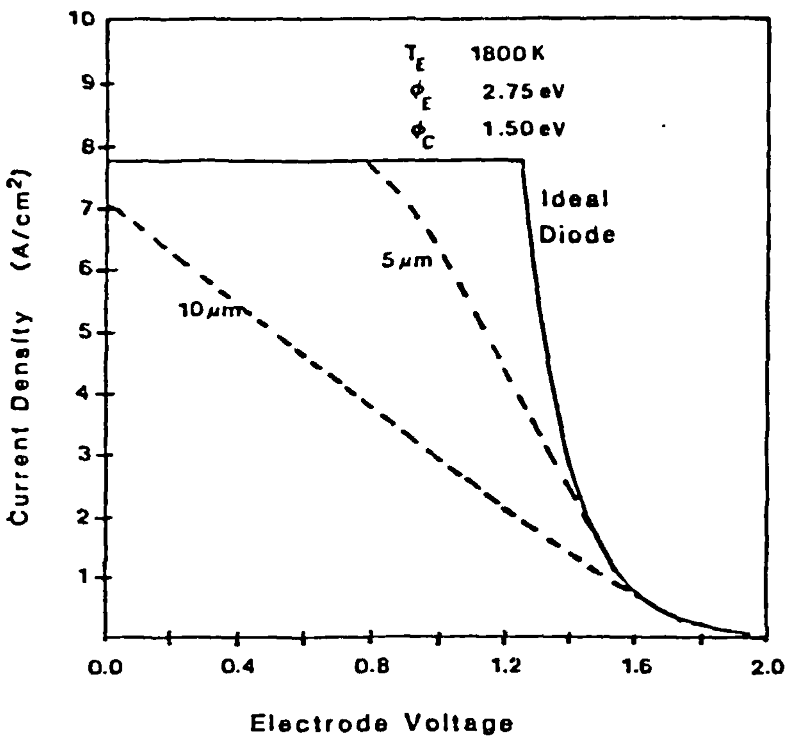


Fig. 3 Dependence of Vacuum Diode Volt-Ampere Characteristics on Spacing

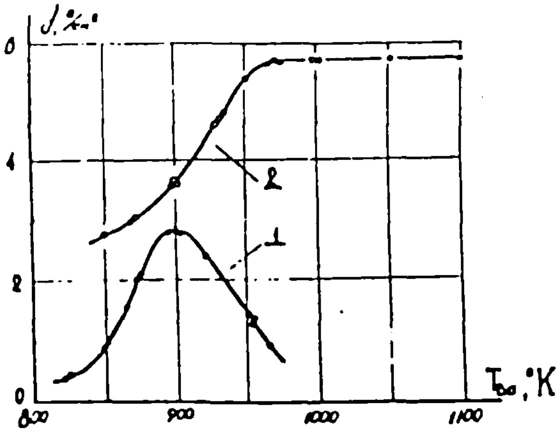


Рис. I. Зависимости плотности тока насыщения для гладкого (I) и развитого (2) катодов от температуры бариевого термостата.
$T_к$ =1970°К; P_{Cs} = $2\cdot10^{-2}$ тор; d = 0,3 мм.

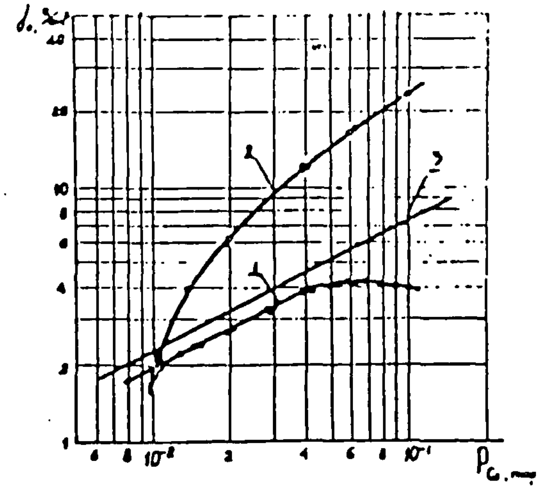


Рис. 2. Зависимости максимальных токов j_0 от давления паров цезия для $T_к$ =1970°К; d =0,3 мм; I – гладкий катод; 2 – развитый катод; 3 – расчет $Kn \gg I$, $j_0 \sim (P_{Cs})^{1/2}$.

Fig. 1. Saturation current density for smooth cathode (1) and for developed cathode (2) as functions of barium thermostat temperature
T_c = 1970° K; $P_{Cs} = 2\cdot10^{-2}$ torr; d = 0.3 mm
Key: A. j, A/cm^2

Fig. 2. Maximum current j_0 as functions of cesium vapor pressure for T_c = 1970° K; d = 0.3 mm
1. Smooth cathode
2. Developed cathode
3. Calculation Kn [Knudsen number] >> 1, $j_0 \sim (P_{Cs})^{1/2}$.

Key: A. j, A/cm^2
B. P_{Cs}, torr

Fig. 4 Soviet Experimental Results for Planar and Structured Emitters

with a structured emitter is as much as three times greater than for an equivalent converter with a planar emitter. There is at present no definitive explanation for these results. This effect could be extremely important to practical thermionic energy conversion. Output power density for the Soviet converter in the Knudsen mode was better than typical ignited mode converters for emitter temperatures above 1900 K, implying that an output with nearly half the output current density and up to twice the voltage, and a much higher efficiency.

One proposed explanation [8] was that excited state barium atoms, produced on the emitter surface, can associatively ionize with excited state cesium ions to produce the dimer ion $BaCs^+$. This would provide a large additional source of positive ions which would explain this and other anomalous results [9] in barium-cesium-filled converters.

An alternative explanation was that the emitter geometry increases trapping of emitter positive cesium ions. This results in a more ion-rich condition in the interelectrode plasma, so that the plasma is slightly more positive, enabling a larger fraction of the emitted electron current to be conducted.

The last phenomena to be studied were interaction effects between adjacent converters. As presently conceived, a SAVTEC system consists of a large number of converters in a common cesium-containing spaced with the converters connected in a series-parallel array. The difference in potential between converters connected in series might lead to parasitic discharges and other, unexpected interactions between converters.

1.2 WORK STATEMENT

1st Year:

Task 1 - Experimental Apparatus

Devise a demountable experimental apparatus for multiple investigations of different SAVTEC types of converter structures. Prepare SAVTEC converters.

Task 2 - Data Acquisition Experiments

Investigate Knudsen discharge operation regime with thermal ion emission from emitter electrodes.

Task 3 - Modeling

Formulate a composite analytical model which can deal with collisional and collisionless discharge regions in the same cesium space.

Task 4 - Analysis and Reporting

Submit report at end of first year.

2nd Year:

Task 1 - Data Acquisition Experiments

Continue thermal ion emission regime experiment. Investigate operation with very close electrode spacing. Determine effects of emitter structuring and mixed vapor operation.

Task 2 - Experimental Apparatus

Prepare barium-compatible SPC converters. Modify test stand for barium reservoir and additional converter envelope heating.

Task 3 - Modeling

Formulate a two-dimensional model of Knudsen mode plasma to investigate phenomena associated with emitter structure. Investigate associative ionization in a mixed barium-cesium vapor.

Task 4 - Analysis and Reporting

Compare results of experiment and modeling. Submit report at the end of the second year.

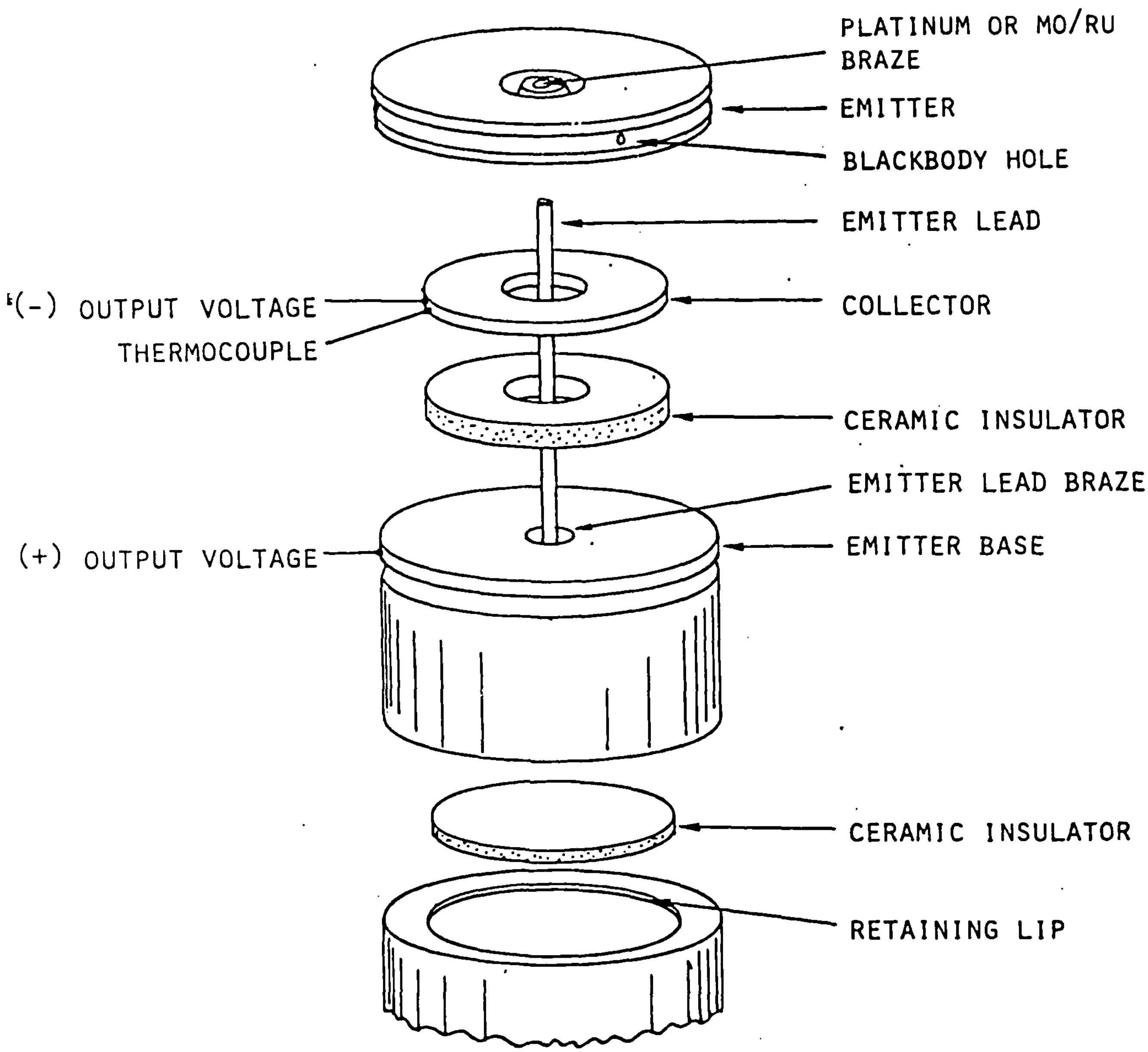


Fig. 5 SAVTEC Thermionic Converter

2.0 Close-Spaced Knudsen-Mode Thermionic Converters

2.1 Experiments with SAVTEC Electrode Structures

2.1.1 Introduction:

SAVTEC (Self-Adjusting, Versatile Thermionic Energy Converters) devices consist of a series-parallel multidiode array of very small thermionic converters whose narrow gap spacing is established by thermal expansion of the emitter support/electrical lead. The SAVTEC concept is based on the use of distributed electrodes within a single cesium enclosure. Heat transfer to the multiplicity of emitters was by radiative coupling from the top surface of the enclosure in the original concept. More recently, concepts have been proposed using small in-core nuclear-fueled emitters. A diagram of a single experimental SAVTEC diode of the type used in this program is shown in Fig. 5. The center post electrical lead is intended to result in heat conduction radially inward toward the emitter center. This results in slightly higher temperature at the outer edge of the emitter putting the electrode in tension and causing it to flatten.

Under DOE sponsorship a nineteen-cell SAVTEC array was constructed and tested with a flame-heated enclosure [10]. Up to seventeen of the originally shorted elements could be unshorted by thermal expansion.

2.1.2 Objectives

The experimental objectives were as follows:

a. To demonstrate and characterize the performance of a SAVTEC diode structure in the quasi-vacuum mode of operation. In this mode the interelectrode spacing is extremely small (<10 μm) and the emitter temperature is low (<1500K). Cesium vapor is introduced into the interelectrode space only to reduce the electrode work functions. The experimental data was to verify the performance expected from space-charge theory and demonstrate the ability to achieve the necessary interelectrode spacing.

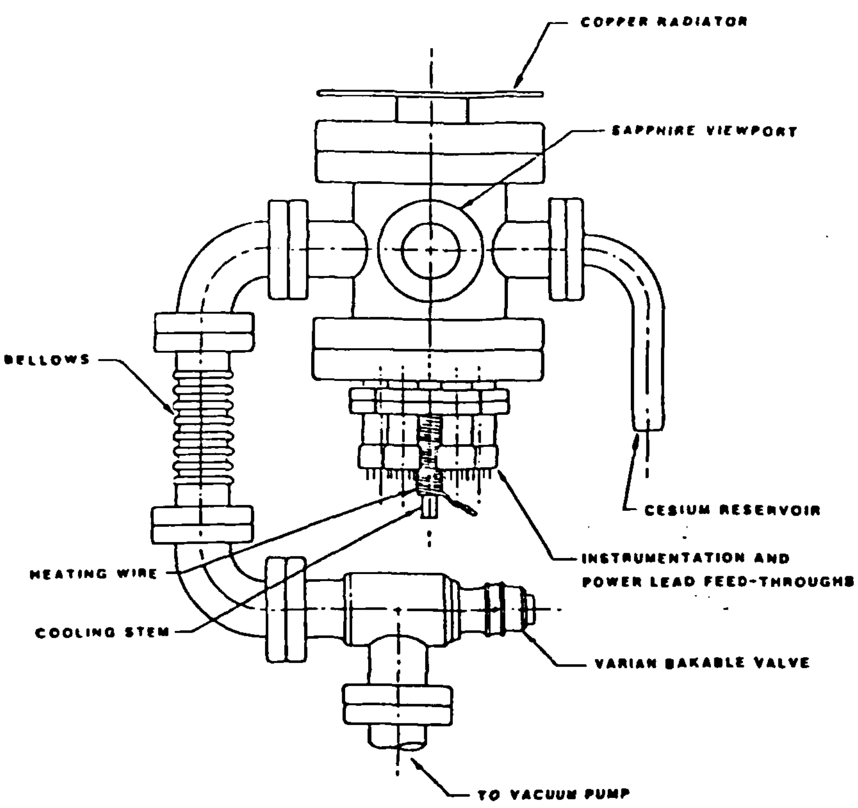
b. To characterize the performance of a SAVTEC diode in the unignited mode and the transition region between quasi-vacuum and unignited operation. In this mode the interelectrode spacing can be larger (up to 50 μm) and the emitter temperature is high (>1500 K). Space charge is reduced or eliminated by cesium ions generated on the emitter surface. Higher cesium pressure increases the maximum output power up to the point where electron-atom scattering becomes significant. A small interelectrode space reduces scattering losses and allows operation at higher cesium pressures resulting in a higher output power density.

c. To examine interaction effects between adjacent SAVTEC cells or between SAVTEC cells and the cesium enclosure. Series connection of cells would result in cells of different potential within a common cesium vapor space, possibly resulting in arc breakdown between cells. A deliberate arc generated between the heated portion of the cesium enclosure and the converter emitters has been suggested as a method of generating auxiliary ions in order to increase converter performance.

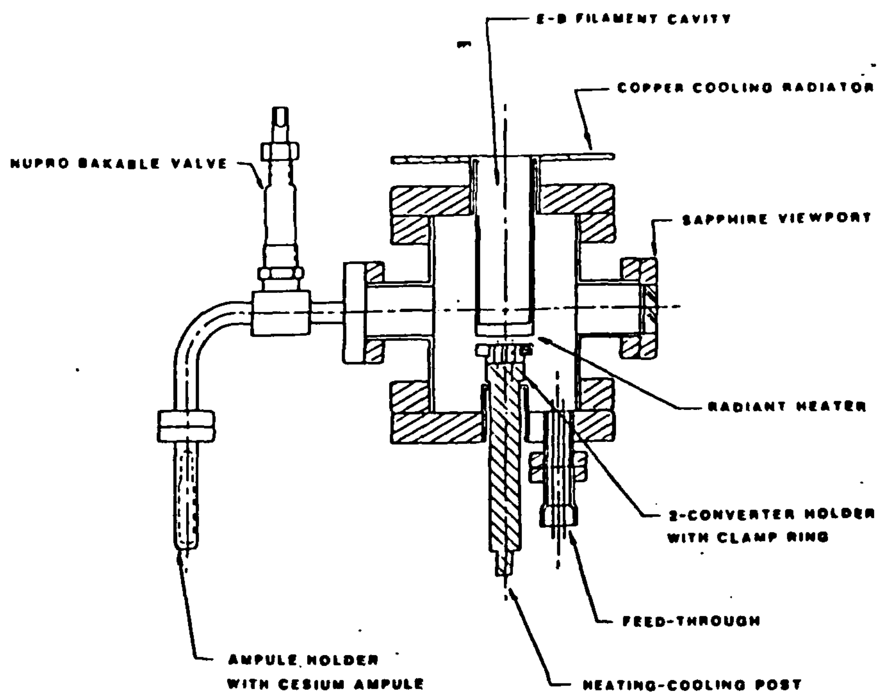
2.1.3 Experimental Apparatus

An instrumented test chamber for SAVTEC converters have been constructed. Diagrams of the chamber are shown in Fig. 6. The chamber is equipped with radiant heating for the SAVTEC emitters, and a temperature-controlled, liquid-cesium reservoir to provide cesium vapor. The entire chamber can be heated to 400°C in order to prevent cesium condensation. Two SAVTEC converters are mounted side by side on a temperature controlled post. A diagram of an experimental SAVTEC is shown in Fig. 5. Current leads, voltage probes, and collector thermocouples are connected to the converters. Emitter temperature measurements are made through a sapphire window using optical pyrometry.

Four SAVTEC converter structures have been constructed. The first two had tungsten emitters, molybdenum collectors, and a tungsten-26% rhenium lead. These were designed to be clamped into the converter mounting post. Testing showed that collector cooling was inadequate with this design. The second two SAVTECs were designed to be brazed into the post. These had



EXTERIOR VIEW OF SAVTEC TEST CHAMBER



SECTIONAL VIEW OF SAVTEC TEST CHAMBER

Fig. 6 Diagrams of SAVTEC Test Chamber

molybdenum emitters and molybdenum collectors. The lead material was changed to rhenium in order to get a greater interelectrode gap by thermal expansion. This was because only one of the previous set of converters unshorted upon heating. In order to obtain data in the high-emitter temperature, unignited-mode regime, the test chamber was modified for better collector cooling, with brazed-in converters and shielding of the collector from the radiant heat source. Because the heater to emitter temperature drop was about 400 ^{o}C, a welded tungsten radiant heat source assembly was substituted for the brazed molybdenum one in order to achieve higher radiant heater temperatures.

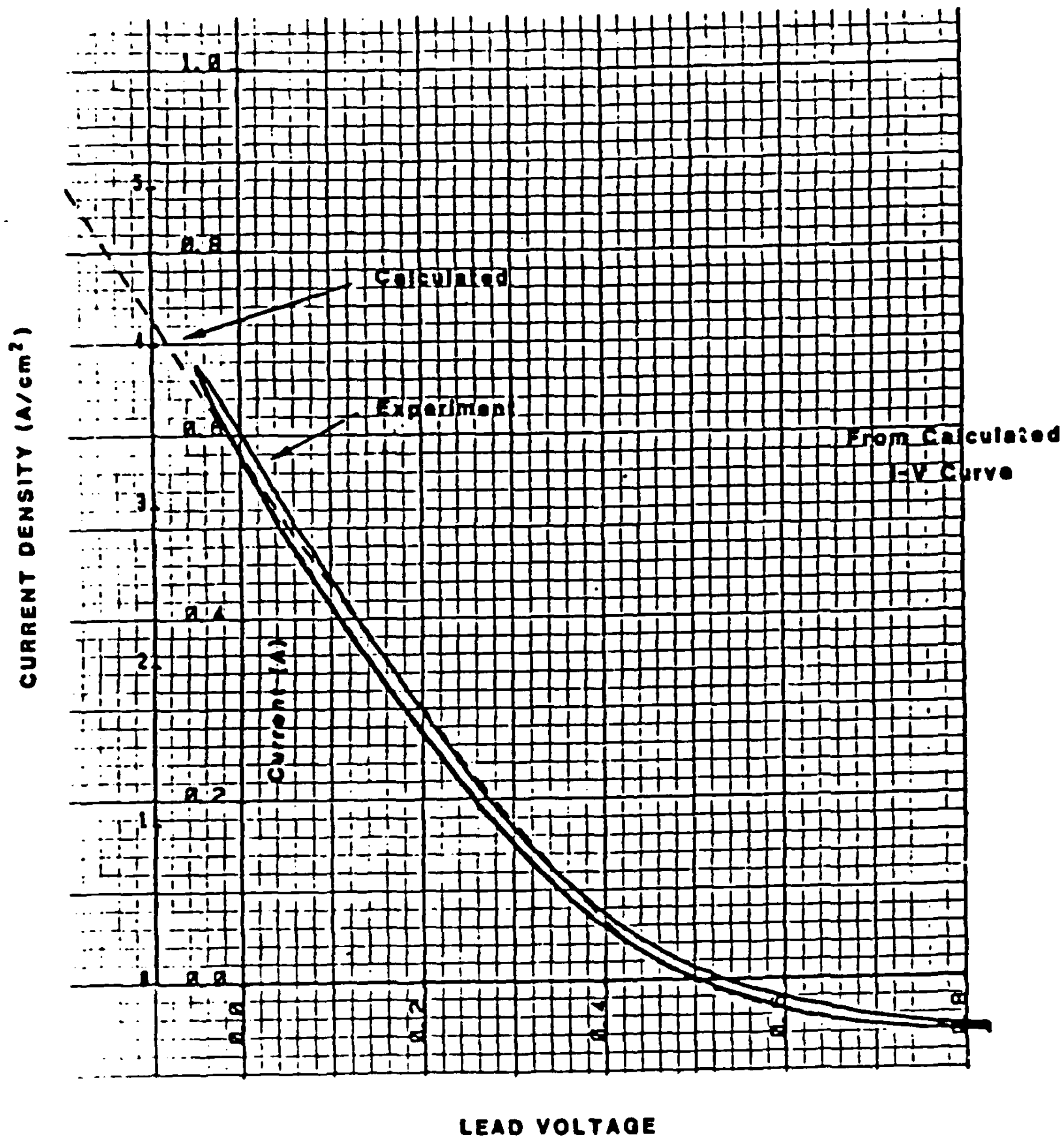
2.1.4 Experimental Results

Two SAVTEC converters were tested in the chamber. Volt-ampere characteristics were obtained from one of these. Operation at emitter temperatures higher than 1250 K was prevented by an excessive rise in collector temperature. This caused thermal expansion of the collector which would short the converter.

The agreement between the experimental and theoretical results is shown in Fig. 7. For the case shown the interelectrode spacing which gave best agreement was 6.5 μm (0.25 mils).

During the second year of the program, an experiment was conducted to operate a SAVTEC diode in the thermal ion source regime, or "unignited" mode. This diode was designed to have an interelectrode spacing larger than the 6.5 micron gap converter tested in the first year of the program. Both the emitter and collector were made of polished polycrystalline molybdenum. Emitter heating was by a tungsten radiator positioned over the diode as in previous experiments.

Comparison of the results to theoretical models indicates an operating electrode gap of 18-22 microns, depending on emitter and collector temperatures. This is consistent with thermal expansion calculations. The diode was tested at emitter temperatures up to about 1700 K. Operation at higher temperatures was prevented by shorting of the diode and by difficulty



EMITTER :	TUNGSTEN	
COLLECTOR :	MOLYBDENUM	
EMITTER TEMPERATURE :		1170 K
COLLECTOR TEMPERATURE :		800 K
CESIUM RESERVOIR TEMPERATURE :		507 K
EMITTER WORK FUNCTION :		1.66 eV
COLLECTOR WORK FUNCTION :		1.56 eV
ELECTRODE SPACING :		6.5 μm
COLLECTOR AREA :		0.174 cm^2
LEAD RESISTANCE :		~30 mΩ
BYPASS RESISTANCE :		~13.5 Ω
MAXIMUM OUTPUT POWER DENSITY :		0.35 W/cm^2

Fig. 7 Comparison of results from experiments theoretical model

in operating the radiant heater at higher than 2300 K. The diode shorting at higher emitter temperatures was reversible, and its cause is not known.

Measurements of maximum output power for the diode tested in the second year (SVT-3) and the diode tested in the first year (SVT-1B) are shown in Fig. 8 as a function of emitter temperature. At low temperatures maximum power is very well predicted by a simple "vacuum" mode calculation involving only electrons. This is not surprising since good agreement is achieved in this regime between calculated and experimental volt-ampere curves. For emitter temperatures above about 1580 K the SVT-3 diode begins to follow predictions of unignited mode theory involving compensation of space charge by surface-generated ions. That a diffusion-based theory can describe the diode behavior so well is due to the fact that, in the unignited mode, maximum power occurs at cesium pressures high enough to give an electron mean-free path on the order of the interelectrode gap. In this regime the diode is no longer operating in the Knudsen mode but is not yet in the collision dominated diffusion mode. Diffusion theory suggests the approximation of reducing the current density predicted by a collisionless model by the factor $1/(1+.75\ d/\lambda_e)$, where λ_e is the mean-free path and d is the gap. When this is done, the computed volt-ampere curves agree very well with experimentally measured curves, and the computed maximum power makes a smooth transition between the vacuum mode theory and the unignited theory.

Emission characteristics of the emitter and visual observation indicate that a layer of cesium oxide was formed on the inside of the test chamber due to a small leak. The measured Rasor-Warner plot of the emitter work function vs the ratio of emitter temperature to cesium reservoir temperature is shown in Fig. 9. The data lie between previously measured curves for clean molybdenum and single crystal (110) molybdenum with about 10^{-4} torr of cesium oxide. Although introduced inadvertently, the oxygen has a beneficial effect, reducing the cesium pressure necessary to achieve a given emitter work function. Based on the interelectrode gap and the measured work function dependence on T_E/T_R, theory predicts that if the emitter temperature of SVT-3 could have been raised, the diode would have reached a peak power output of 10-12 watts/cm^2 at about 1950 K emitter temperature. Above this temperature, the electron space charge would be overcompensated

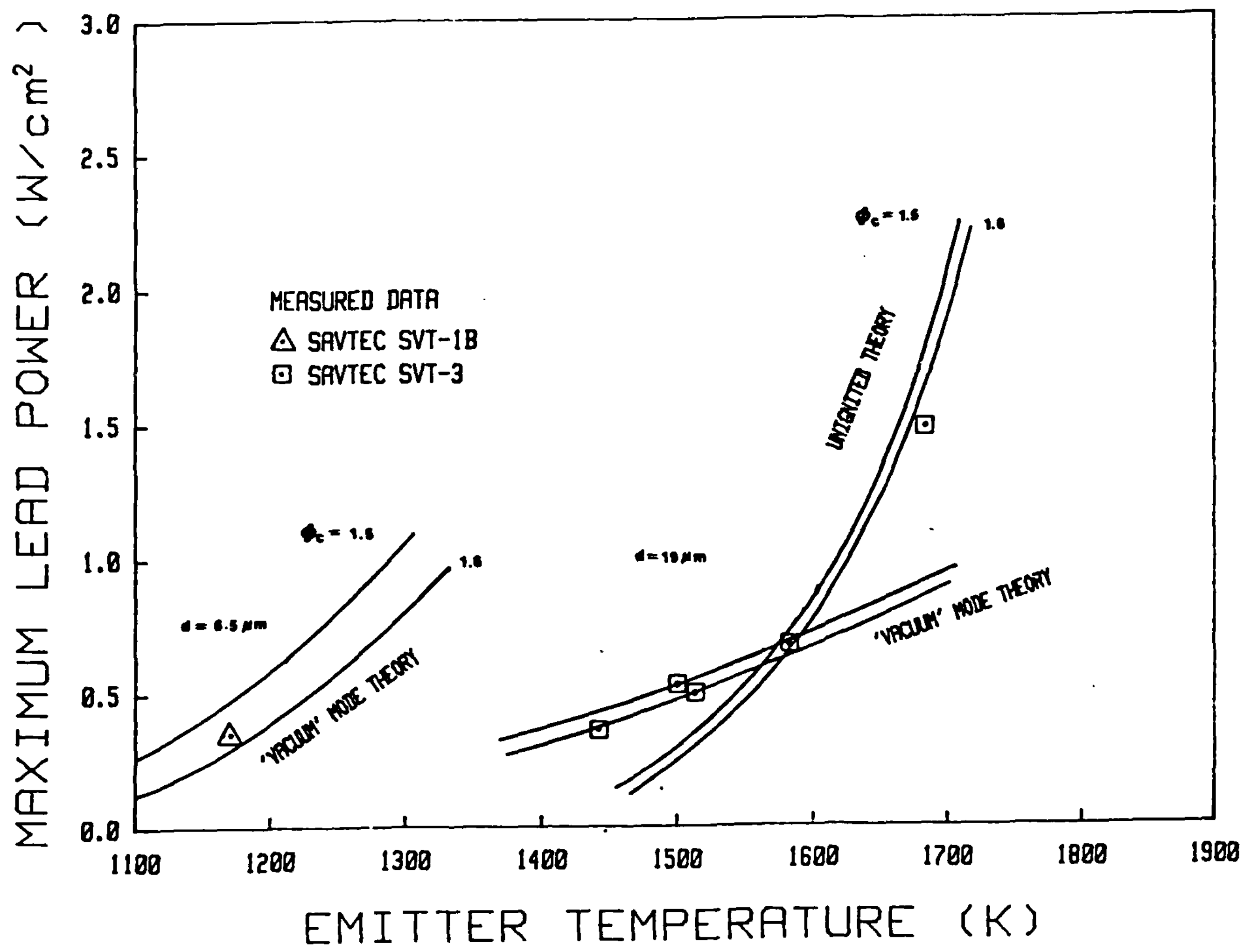


Fig. 8 Experimental and Theoretical Output Power Densities from SAVTEC Converters

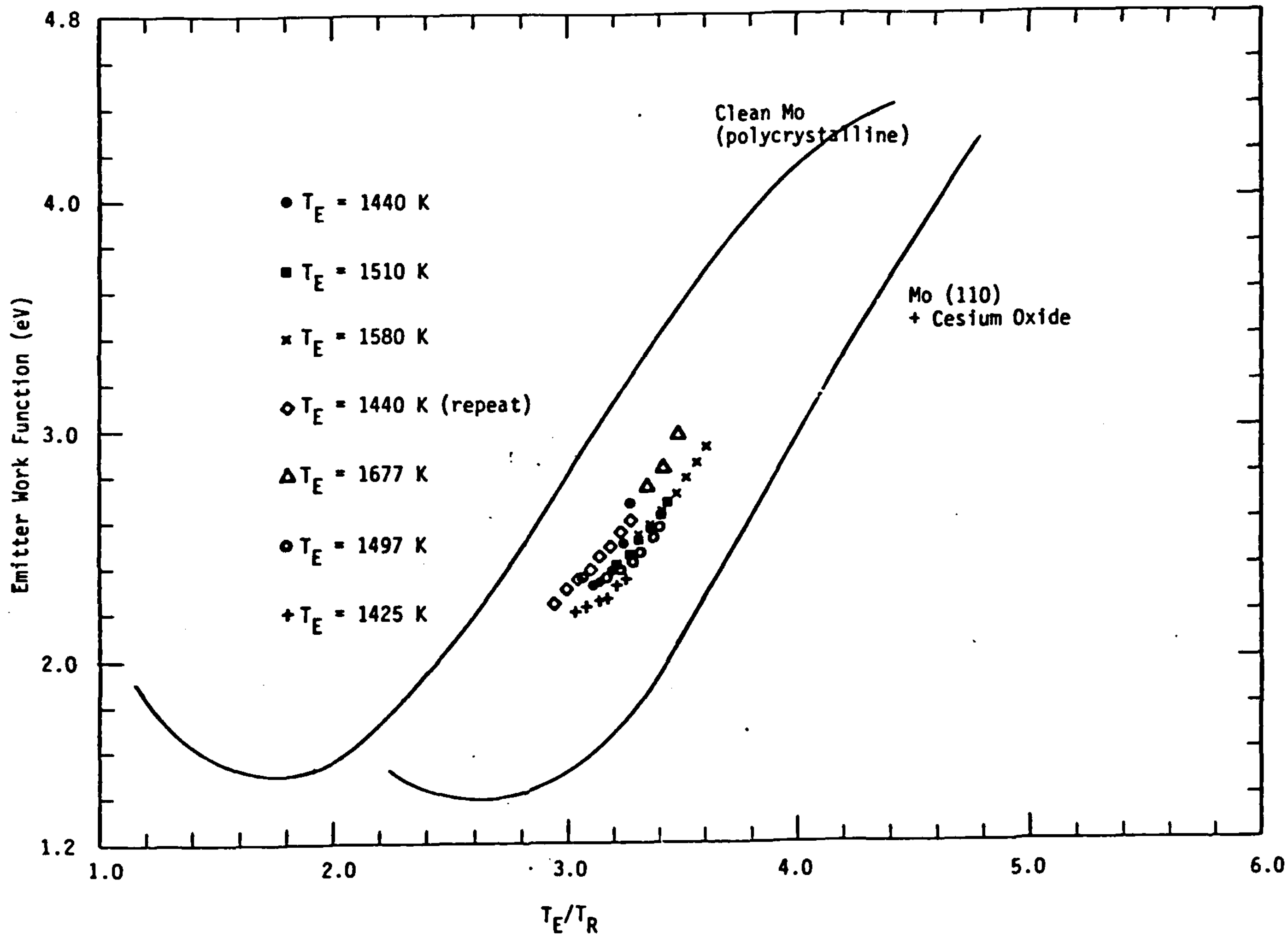


Fig. 9 Measured Emitter Work Function from SVT-3 Showing Oxygen Effect

by ion emission. Maximum output power would then fall due to the decrease in electron emission current as emitter temperature is increased.

Efforts were made to measure the effect of ions produced in an auxiliary discharge between the radiant heater and the emitter. Unfortunately, the discharge could not be confined to a small region, and occurred between the chamber structure and the collector as well as between the radiator and emitter. The current from this discharge masked any measurement of the effect of auxiliary ion transport. Eliminating spurious discharges would have meant a significant amount of alteration to the test chamber. Based on this and the results of the theoretical analysis done in the first year of the program, which predicted only very small effects, it was decided not to continue this effort.

2.2 Analytical Modeling of Close-Spaced Thermionic Converters

2.2.1 Objectives

a. To produce a comprehensive analytical model of a Knudsen-mode, close-spaced thermionic diode. The model is intended to analyze and predict performance in the quasi-vacuum and unignited modes as well as the transition between these. The effect of an auxiliary source of ions must also be incorporated into the model. Similar descriptions have been developed in the past [11,12], however they ignored the effects of collector back emission and charged particle trapping, as well as considering only a limited number of different possible interelectrode potential distributions.

b. To predict the effect of an auxiliary discharge between the cesium enclosure and the SAVTEC emitters. This involves coupling of a collision-dominated discharge region to the collisionless SAVTEC interelectrode space. The diffusion of plasma formed above the emitters through the space between emitters and then radially into the interelectrode space must be calculated.

2.2.2 Results

A comprehensive computer model, referred to as KMD2, of the Knudsen mode discharge in one dimension has been developed. This model uses the Vlasov (collisionless Boltzmann) equation for charged particle density as a function of potential. These can be substituted into Poisson's equation which is solved for the spatial dependence of potential in the interelectrode gap. A finite difference method is used to numerically integrate Poisson's equation. Electron and ion currents can be calculated once the potential is known. The solution algorithm is diagrammed in Fig. 10. Thermionically emitted electrons, positive cesium ions, back emitted electrons from the collector, and auxiliary ions are included in the formulation. Expressions for trapping of charged particles in potential wells due to infrequent collision have been included. These have been found to be important to the formulation. The effects of ion trapping under electron-rich (incomplete-neutralization of space charge) conditions are summarized in Fig. 11. For a close-spaced diode ($d<50\ \mu m$) the effect is an increase in current density near the maximum output power in the cases studied than for characteristics calculated without ion trapping. For conventionally spaced diode ($50\ \mu m<d<0.5$ mm) the effect is independence of the apparent saturation current density from emitter work function in the electron-rich regime. Without ion trapping the saturation current goes through a maximum as the work function is decreased and then falls off as the work function is decreased further.

The analysis of collisional discharges has been addressed using computer models of the unignited (ions generated by surface ionization) and ignited (ions generated by collisions) modes. These models have been developed by Rasor Associates prior to this contract, and have been extensively used to analyze thermionic phenomena in these modes. They have been used to calculate the ion and electron currents into the region surrounding the SAVTEC electrodes as a function of applied potential between the heat source and the emitter.

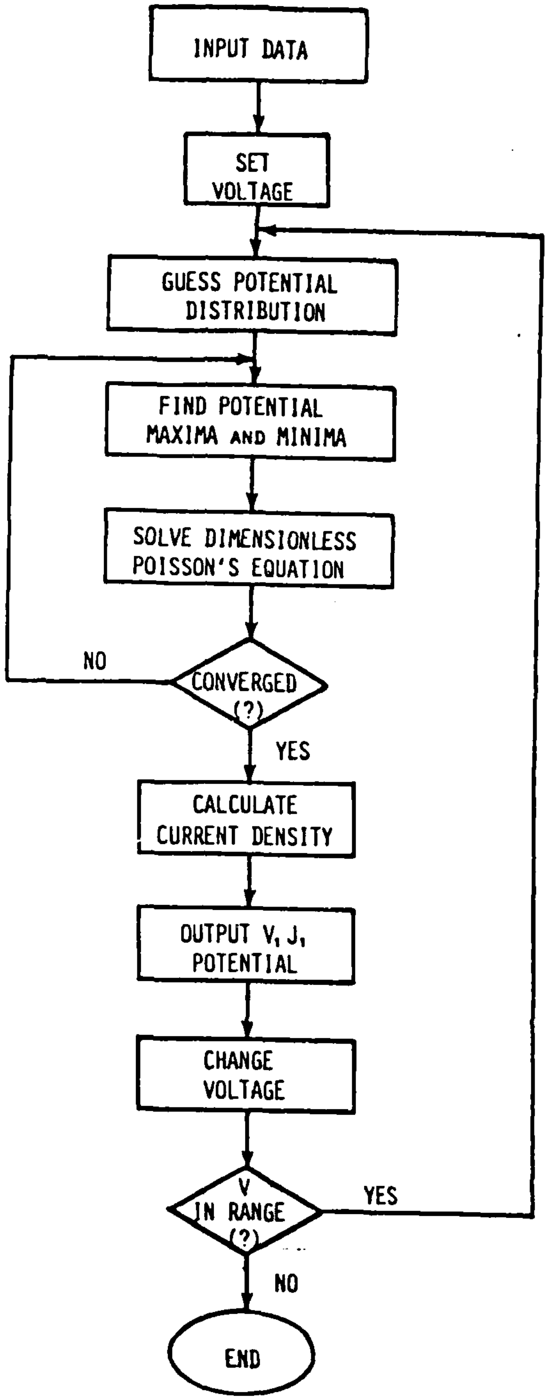


Fig. 10 Algorithm for KMD-2 Computer Model

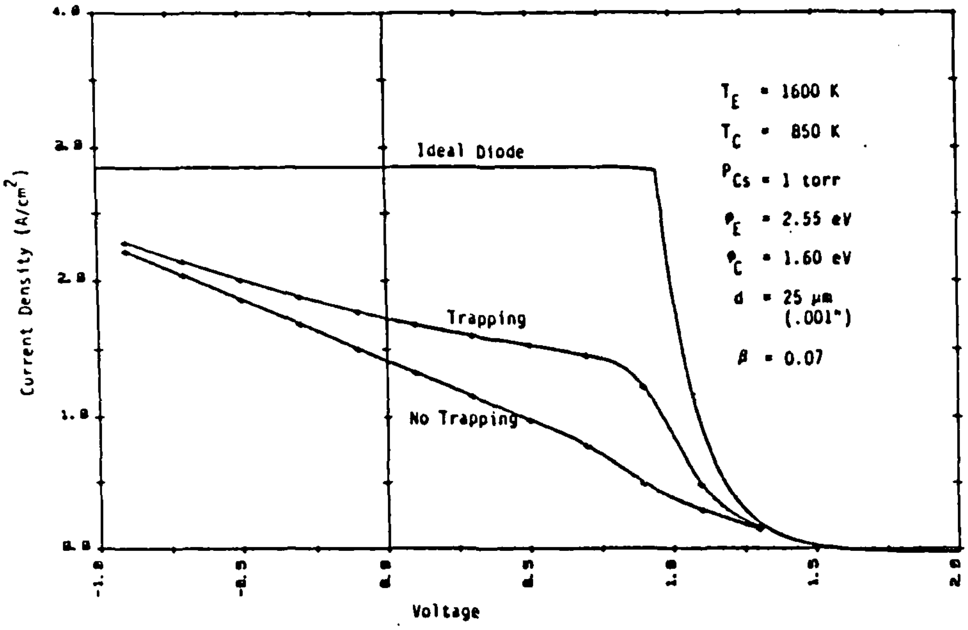


Fig. 11a Increase in current density near maximum power point due to positive ion trapping in a close-spaced diode

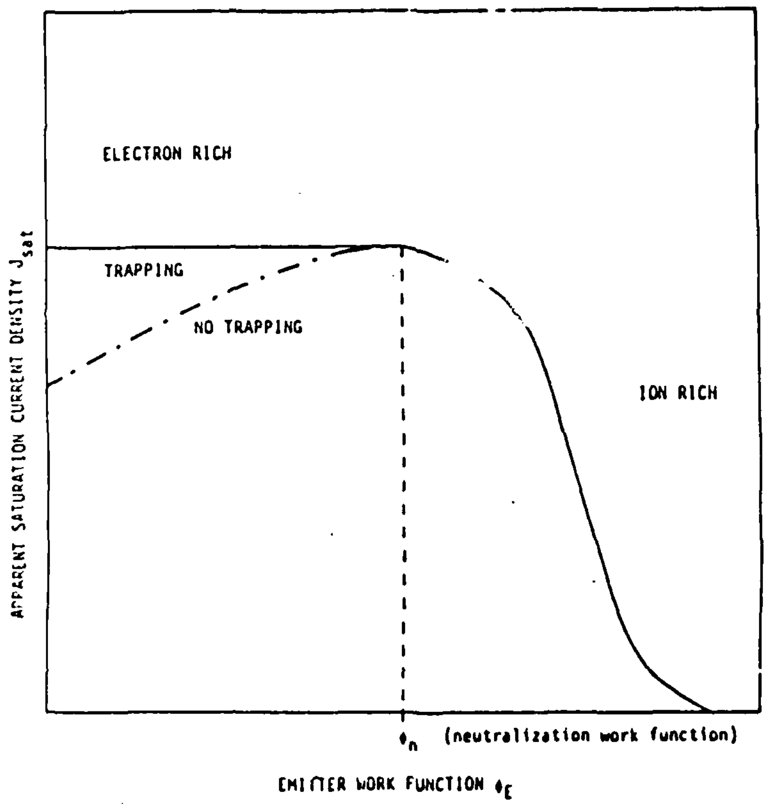


Fig. 11b Independence of apparent saturation current density from emitter work function due to trapping in a conventionally-spaced diode

An analytical expression was derived from diffusion theory which relates the ion density at the outer edge of two plane-parallel electrodes to the radially averaged ion density in the interelectrode space. This gives a value for the ion density term used in the Knudsen mode computer model, which can then predict the observable effect on output characteristics. A diffusion analysis has been used to compute the plasma density at the edge of a close-spaced electrode structure given the electron and ion current into this region. Results show that for the auxiliary ion source to be effective the ratio of electrode radius to interelectrode gap R/d must be less than about $\sqrt{50\ \lambda_i/d}$ where λ_i is the ion mean-free path. The ratio in the experimental SAVTEC structure used in this program is about 2.5 to 5 times larger than this value, so only a small performance effect is predicted. The electrodes would have to be about 2 mm in diameter in order to obtain a large effect.

2.3 Summary

Conclusions of this research are as follows:

1. Performance of the converter at low emitter temperature is well predicted by collisionless space-charge theory.

2. Maximum performance in the unignited mode at higher emitter temperatures occurs between the Knudsen and diffusion modes, however, existing analytical models can be readily extended into this region to predict performance.

3. Transition between the vacuum and unignited modes shows no increase in maximum output power due to additive effects of space charge compensation by close spacing and by ion emission.

4. The SAVTEC type diode structure shows promise as a menas of obtaining thermionic energy conversion with interelectrode

spacings less than 25 microns (1 mil). Additional development work on fabrication and design will be required to eliminate the shorting problem before the design can be used in practical systems.

3.0 STRUCTURED EMITTER KNUDSEN-MODE THERMIONIC CONVERTERS

3.1 Barium/Cesium Planar Diode Experiment

3.1.1 Objective

The purpose of the structured emitter experiment was to verify and explain the anomalously high performance observed in Ref. 1 when a Knudsen mode thermionic converter was operated with such an emitter. In that experiment a mixed vapor of barium and cesium was used in the interelectrode space. In such mixed vapor converters the cesium vapor provides positive ions by surface ionization on the emitter and the barium vapor controls the reduction of the electrode work functions. Experimental results revealed a factor of four increase in maximum output power density and a factor of six increase in maximum current density over an identical converter with a smooth emitter.

Three tasks were planned in this contract to examine the structured emitter effect. The first was an experiment using a variable spacing planar converter equipped with a structured emitter and modified to use both barium and cesium. An analytical model of the structured emitter effect was also formulated. Additionally, the possibility of anomalous effects due to associative ion formation between excited state atoms of barium and cesium had been proposed as a mechanism for the effect [8]. This hypothesis was briefly examined.

3.1.2. Experimental Apparatus

This task involved construction of a variable-spacing, planar converter and test-stand which would enable the converter to be operated with a mixture of cesium and barium vapors. Use of barium vapor additive

presents many problems, in particular, the severe materials compatibility restrictions, the necessity to operate the converter envelope at greater than 800 $^{\circ}$C, and the backstreaming of barium into the colder cesium reservoir. The advantage is that its use allows completely independent control of the emitter work function, which is controlled by the barium pressure. The ion emission is controlled by the cesium pressure. Further, the required total pressure is low enough so that Knudsen mode conditions can be achieved even at spacings as high as 1 mm.

Published literature on previous barium/cesium converter experiments was reviewed and two previous investigators in this field were contacted for personal discussions. A barium chemical compatibility test was also performed on several materials to supplement the data available from these previous experiments.

The creation of a metal-to-ceramic seal which is resistant to barium, can operate at 800 $^{\circ}$C, and allows variable electrode spacing proved to be extremely difficult. Instead, it was decided to use a resistive metal bellows between the emitter and collector. Provisions were made to compensate for the bypass current passing through the bellows in order to measure the actual current flowing between the electrodes. The structured emitter used a spiral groove 0.05 mm wide by 0.6 to 0.8 mm deep. The is very close to the structure geometry used in Refs. 6 and 7. Initial attempts to fabricate the emitter out of pure tungsten by using a reactive ion etch method were unsuccessful. The emitter was finally made using the procedure briefly outlined in Ref. 7, in which ribbons of tungsten and molybdenum are wrapped tightly together, brazed into a cup at very high temperature, and ground flat. The molybdenum is then chemically etched to the desired depth using an etchant which does not affect tungsten. Photographs of the emitter are shown in Fig. 4.

A photograph of the assembled converter is shown in Fig. 12. Some difficulty was encountered in welding the stainless steel bellows to the molybdenum converter enclosure, which necessitated a complex transition piece and the use of a brazing material which was known to have only moderate resistance to attack by barium vapor. Problems due to this design

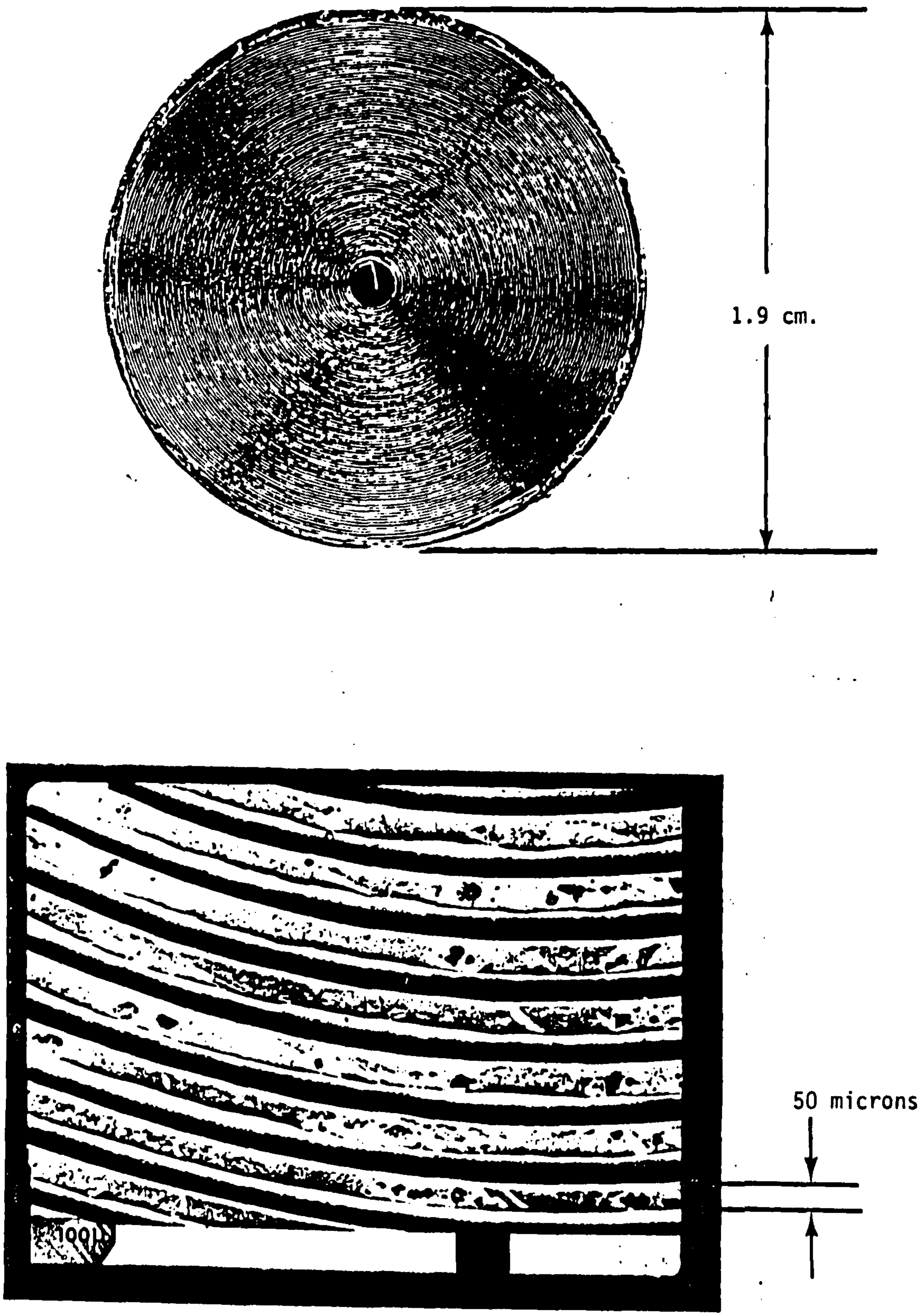


Fig 12 Structured Emitter

are discussed in the next section. The barium and cesium reservoir were connected to the converter by titanium tubes. A small orifice was placed between the two reservoirs in order to minimize the loss of barium into the cesium reservoir, as in Ref. 9. The converter was designed to be outgassed at high temperature with the barium and cesium in place and then sealed by pinching off two tantalum tubes.

3.1.3 Experimental Problems

Difficulties were encountered which prevented obtaining data from the experiment. These were:

1. During high-temperature outgassing, cracks developed in the welds between the stainless steel bellows and the Kovar transition rings which were used to facilitate joining of the bellows to the molybdenum converter housing. The transition piece was necessary due to the impracticality of obtaining a bellows formed of material which could be welded to molybdenum. As a result of the cracks, the converter interior leaked up to a pressure of about 0.1 torr, possibly oxidizing the cesium and barium reservoirs. The cracks were repaired and the converter was again evacuated, however, it was not possible to replace the cesium or barium due to time and funding constraints.

2. The converter was to be sealed using tantalum pinch-off tubes due to the difficulty of constructing valves which could tolerate barium and high temperatures. These pinch-offs had previously been tested, both before and after heating, and had shown that they could be sealed reliably. In the experimental design, however, the pinch-off area was subject to a bending moment which caused the tubing to tear as it was being pinched off. As as result, the converter leaked to full atmospheric pressure when the first of two pinch-offs was made. The tube was repaired by welding and the converter again evacuated through the remaining pinch-off tube. The

final pinch-off was shown to be leak-tight by post-operation inspection.

3. As a result of the difficulty of construction of the converter and the complexity of the vacuum test stand, the available funding was inadequate for construction of a second converter or repair of the existing converter.

3.1.4. Experimental Results

Although the cesium and possibly the barium reservoirs had very likely been partially oxidized, it was decided to proceed with testing the converter. Results at an emitter temperature of 1970 K showed saturation currents below 0.5 A/cm^2, with very little effect of barium reservoir temperature. This is well below currents expected even from a smooth emitter, based on previous barium/cesium experimental results. There were some indications from the observed performance that the converter was "gassy". Some difficulties were also encountered in compensating for the bypass current in the metal bellows. These problems were compounded by failure during testing of the electron bombardment filament for heating the emitter. This necessitated removal of the converter from the test stand and exposure to atmosphere. Post-operation examination of the converter showed significant oxidation of the cesium and very little evident oxidation of the barium.

3.1.5. Summary

Experimental difficulties prevented successful testing of a structured emitter Knudsen mode converter in this program and thus the results of Refs. 1 and 2 cannot definitely be confirmed at this time. However, the fact that the authors of Refs. 1 and 2 reported repetition of their results, and the support given to these results by theoretical analysis (see section 3.2.3 of this report) indicate a very high degree of probability that the beneficial structured emitter effect is genuine. The work done on this experiment has provided valuable experience with the fabrication techniques necessary for constructing a test converter, in particular it has shown that

experimental emitters with the required structure can be easily made. Advanced methods which have come to light since the end of this project could produce a barium-resistant, high-temperature metal-to-ceramic seal. In view of these factors, it would be entirely feasible to build a workable test device to verify and explore the structured emitter effect in a Knudsen mode thermionic converter. In view of the present importance of very high temperature "Sprint-mode" space nuclear power, this experiment should still be performed.

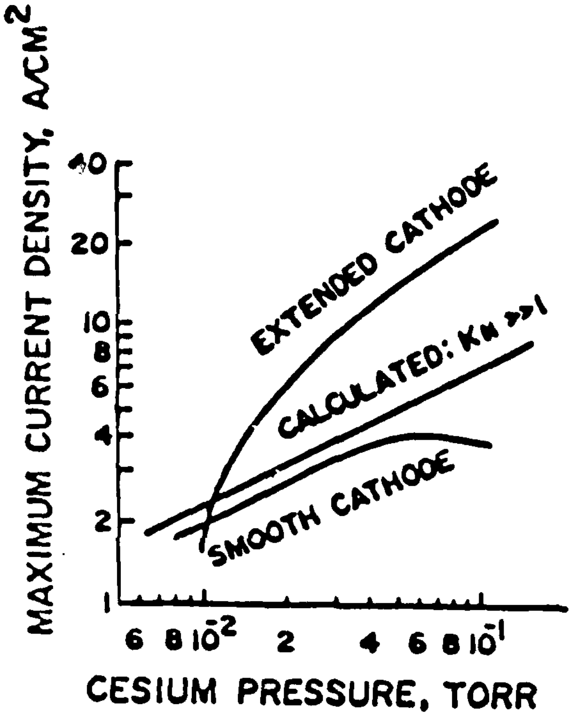
3.2 Analytical Modeling of Structured Emitter, Mixed Vapor Converters

3.2.1 Investigation of Associative Ionization in Mixed Cesium and Barium Vapor

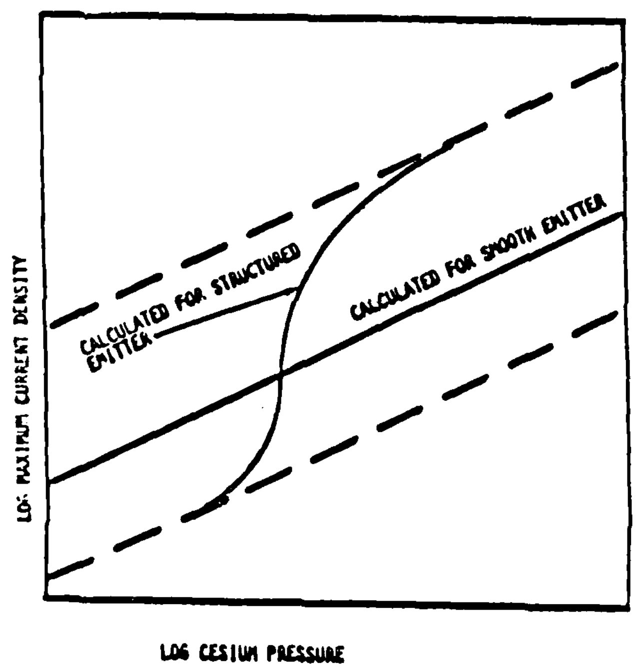
Due to lack of knowledge about the dissociation energy and ionization potential of $BaCs^+$ it is impossible at this point to say if the formation of $BaCs^+$ from collisions between excited state atoms is energetically favorable. The analysis we used assumed that the process is energetically allowed. The population densities of Cs(6P)and Ba(3D) were estimated for unignited mode conditions, as were the collision rates between the two. The results indicated an insignificant formation of $BaCs^+$. Also, analysis of data from Soviet barium/cesium thermionic converter experiments [13] indicates the barium does not play a significant part in positive ion formation.

3.2.2 Investigate Phenomena Associated with Emitter Structure in the Knudsen Mode.

An elementary phenomenological analytical description has been formulated for Knudsen mode thermionic converter operation with a slotted emitter. Such a description provides intuitive comprehension of the dominant physical mechanisms, and assist characterization of experimental data and the results of more general and exact numerical analysis based on the fundamental transport equations. First, an elementary description of the Knudsen mode with smooth electrodes was formulated. This elementary analytical model accurately describes the observed dependence (Ref. [6]



Experimental Results from Dunaev, Babanin, Mustafaev, Sitnov, and Ender, Sov. Phys. - Tech. Phys. 20,938,1976.



Calculated Maximum Current Density Taking Directed Ions into Account

Figs. 1 and 2) of the saturation output current density on emitter work function and on cesium pressure in the collisionless regime.

This successful approach was extended to the slotted emitter by assuming that the ion current from the slots consists of two ion groups: a group with fully randomized orientation (corresponding to the equilibrium Saha-Langmuir current from the opening of the slots), and an oriented group directed out of the slots. The oriented group arises from a portion of the random Saha-Langmuir ion current across the slots becoming trapped into the slots by being scattered out of the escape cone of their walls via small angle scattering. This model qualitatively gives the observed enhanced output current over that for the smooth emitter, and its dependence on cesium pressure, within the uncertainties of the published data. However, the observed assymptotic value of the output current that is approached at high cesium pressure is a factor of two greater than that predicted by the elementary model. Two potentially interrelated aspects of the model might account for this discrepancy are being explored: one concerns that possibility that the plasma potential in the slot may differ from that in the diode gap, and the other concerns considerations of the component of the oriented group of ions that is directed along (rather than out of) the slot.

3.3 Recommendations for Future Work

a. The structured emitter barium/cesium experiment should be performed as previously discussed in order to verify the effect. Planar converters with flat emitters should be used to establish a reference performance level. Structured emitters of different materials should be tested in order to establish the independence of the effect from materials, properties or barium pressure. A ZrC emitter which would require no barium at all might possibly be tried if fabrication techniques can be worked out.

b. The phenomenological description of the structured emitter should be continued and refined in order to quantitatively describe the experimental data.

c. The detailed particle kinetics in the emitter slots should be examined using existing two-dimensional particle simulation computer codes.

4.0 Technical Journal Publications

No technical journal publications were submitted concerning this work.

5.0 Professional Personnel

Mr. John B. McVey - Principal Investigator

Dr. Ned S. Rasor - Project Director

6.0 Interactions

The spoken paper "Ion Trapping Effects in Electron-Rich Unignited-Mode Thermionic Converters" was presented at the 1984 IEEE International Conference on Plasma Science.

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